Measuring the 13-mixing angle and the CP phase with neutrino telescopes

P. D. Serpico and M. Kachelrieß
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), Föhringer Ring 6, 80805 München, Germany
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The observed excess of high-energy cosmic rays from the Galactic plane in the energy range around 10^{18} eV may be naturally explained by neutron primaries generated in the photo-dissociation of heavy nuclei. In this scenario, lower-energy neutrons decay before reaching the Earth and produce a detectable flux in a 1 km^3 neutrino telescope. The initial flavor composition of the neutrino flux, $\phi(\bar{\nu}_e):\phi(\bar{\nu}_\mu):\phi(\bar{\nu}_\tau)=1:0:0$, offers the opportunity to perform a combined $\bar{\nu}_\mu/\bar{\nu}_\tau$ appearance and $\bar{\nu}_e$ disappearance experiment. The observable flux ratio $\phi(\bar{\nu}_\mu)/\phi(\bar{\nu}_e+\bar{\nu}_\tau)$ arriving at Earth depends appreciably on the 13-mixing angle ϑ_{13} and the leptonic CP phase $\delta_{\rm CP}$, thus opening a new experimental avenue to measure these two quantities.

Introduction.—Neutrino physics has progressed enormously in the last decade. The discovery of neutrino oscillations provides the first clear experimental signature for the incompleteness of the Standard Model of particle physics [1]. While the determination of the mixing parameters controlling the solar and atmospheric neutrino oscillations has already entered the precision era, it exists currently only an upper limit for the 13-mixing angle ϑ_{13} from the CHOOZ experiment, $\sin^2 2\vartheta_{13} < 0.1$ [2]. The mixing angle ϑ_{13} characterizes how strong atmospheric and solar oscillations are coupled and therefore also determines the strength of CP violation effects in neutrino oscillations. Among the three possible phases in the neutrino mixing matrix, only the Dirac phase $\delta_{\rm CP}$ enters neutrino oscillations. This phase is at present completely unconstrained. Both the mixing angle ϑ_{13} and the phase $\delta_{\rm CP}$ are observable in solar and atmospheric neutrino oscillation experiments only as subleading, genuine three-flavor effects that are masked mainly by systematic uncertainties [3]. While there are strong experimental efforts to improve the measurements of ϑ_{13} in the near future by dedicated experiments [4], the detection of a non-zero $\delta_{\rm CP}$ appears unlikely for the next generation of facilities [5]. Thus the answer to one of the most interesting questions in neutrino physics, namely the existence of leptonic CP violation, probably has to await the construction of long-baseline experiments using second-generation superbeams or perhaps even a neutrino factory.

In the following, we propose to use high-energy neutrinos produced by decaying neutrons as a new probe to measure ϑ_{13} and $\delta_{\rm CP}$ with neutrino telescopes. The potential of neutrino telescopes to measure the atmospheric mixing angle ϑ_{12} has been discussed recently in Ref. [6], while tests for new physics beyond standard neutrino oscillations using atmospheric neutrino data have been examined in Ref. [7]. Previously, Refs. [8, 9] discussed possibilities to measure or to constrain ϑ_{13} and $\delta_{\rm CP}$ for the case of decaying neutrinos, while the use of the neutron decay channel as neutrino source was suggested in Ref. [10] to test quantum decoherence. Neutron primaries have been invoked to explain an excess of high-energy cosmic rays (CRs) from two regions in the Galactic plane [11, 12]. This signal, in a limited energy range around 10^{18} eV, has been observed by several experiments with different techniques: The AGASA collaboration found a correlation of the arrival directions of CRs with the Galactic plane at the $4\,\sigma$ level [13]. This excess, which is roughly 4% of the diffuse flux, is concentrated towards the Cygnus region, with a second hot spot towards the Galactic Center (GC) [14]. Such a signal has been independently confirmed by the Fly's Eye Collaboration [15] and by a re-analysis of the SUGAR data [16].

Complementary evidence for a cosmic accelerator in the Cygnus region comes from the detection of an extended TeV γ-ray source by the HEGRA experiment [17, 18]. The measured photon spectrum is difficult to explain in terms of electromagnetic acceleration. Also, X-ray or radiowave emission could not be detected by CHANDRA or VLA [19], thus favoring a hadronic accelerator. Similarly, multi-TeV γ-rays from the vicinity of the GC have been recently detected by HESS [20].

Galactic neutron sources.—The excess from the Cygnus and GC region is seen at $E \approx 10^{18}$ eV, i.e. at energies where charged cosmic rays still suffer large deflections in the Galactic magnetic field so that only a neutral primary can produce a directional signal. Another evidence for neutrons as primaries is that the signal appears just at that energy where the neutron lifetime allows neutrons to propagate from a distance of several kpc.

Neutrons can be generated as secondaries either in collisions of high-energy protons on ambient photons and protons, or in the photo-dissociation of heavy nuclei. In the first case, the flux of $\bar{\nu}_e$ from neutron decays would be negligible compared to the neutrino flux from pion decays. Thus one expects a neutrino flavor composition of $\phi_e:\phi_\mu:\phi_\tau = 1:2:0$ before oscillations [33], typical for most sources of high-energy neutrinos. The oscillation phenomenology and signature for such a "standard" GC source were already considered in [21]. In contrast, photo-dissociation of heavy nuclei produces a pure $\bar{\nu}_e$ initial flux. Since the energy fraction transferred to the $\bar{\nu}_e$ is typically $\sim 10^{-3}$ and only neutrons with $E \lesssim 10^{18}$ eV

can decay on galactic distances, the neutrino flux from photo-dissociation is limited to sub-PeV energies. Moreover, the threshold for photo-dissociation on UV photons implies a lower cut-off at $E \sim$ TeV for the $\bar{\nu}_e$ energies.

There are several arguments in favor of the dominance of heavy nuclei in the diffuse Galactic CR flux at $E \sim 10^{18}$ eV. First, the end of the Galactic CR spectrum is expected to consist of heavy nuclei, because the Galactic magnetic field confines more easily CRs with small rigidity. Subtracting the spectrum expected for extragalactic CRs from the measured CR spectrum, Ref. [22] found evidence that the transition between Galactic and extragalactic CRs happens around a few$\times 10^{17}$ eV. In this case, the total diffuse CR flux between $(1-10)\times 10^{17}$ eV consists only of galactic iron nuclei and extragalactic protons. Another method to determine the transition energy is to study the chemical composition of the CR flux [23]. At present, these measurements are not fully conclusive but point to a dominantly heavy component in the CR flux at least up to $\sim 10^{18}$ eV and a possible transition to extragalactic protons at higher energies. Such a higher transition energy would also ease the difficult luminosity requirements needed for extragalactic ultra-high energy cosmic ray sources [24]. Around and above the transition energy, the unconfined flux from Galactic point sources becomes visible. If the flux from these point sources consists of protons or nuclei, has to be answered experimentally for each source separately.

In the following we use as our basic assumption that photo-dissociation of heavy nuclei is the origin of the decaying neutrons. We assume first that other neutrino sources that contaminate the pure $\bar{\nu}_e$ initial flux can be neglected, but at the end we discuss how our conclusions change when this assumption (that can be verified experimentally) is relaxed. To be specific, we use the model of Anchordoqui *et al.* in Ref. [11], who calculated the neutrino flux from the Cygnus region which is in the field of view of the km^3 telescope ICECUBE [25]. These authors estimated an integrated $\bar{\nu}_e$ flux from neutron decays of $\sim 2\times 10^{-11}\text{cm}^{-2}\text{s}^{-1}$ at $E > 1$ TeV by normalizing the neutron flux to the 4% anisotropic component observed by AGASA. This flux corresponds to ≈ 20 events (of all flavors) per year in ICECUBE.

Flavor composition after oscillations.—The fluxes ϕ_β^D arriving at the detector are given in terms of the probabilities $P_{\alpha\beta} \equiv P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$ [34] by

$$\phi_\beta^D = \sum_\alpha P_{\alpha\beta}\phi_\alpha = P_{e\beta}\,\phi_e\,, \tag{1}$$

where we have inserted $\phi_\alpha = (\phi_e, 0, 0)$. Since the galactic distances far exceed the experimentally known oscillation lengths even at PeV energies, the interference terms sensitive to the mass splittings Δm^2's in the usual oscillation formula average-out. Then we can write

$$P_{e\beta} = \delta_{e\beta} - 2\sum_{j>k} \text{Re}(U_{\beta j}^* U_{\beta k} U_{ej} U_{ek}^*)\,, \tag{2}$$

where U is the neutrino mixing matrix and greek (latin) letters are used as flavor (mass) indices.

To obtain a feeling for the dependence of the fluxes on ϑ_{13} and $\delta_{\rm CP}$, we give an expansion of $P_{e\beta}$ up to second order in ϑ_{13} where we use $\vartheta_{12} = \frac{\pi}{6}$ and $\vartheta_{23} = \frac{\pi}{4}$,

$$\begin{aligned} P_{ee} &\approx \frac{5}{8} - \frac{5}{4}\vartheta_{13}^2 \\ P_{e\mu} &\approx \frac{3}{16} + \frac{\sqrt{3}}{8}\vartheta_{13}\cos\delta_{\rm CP} + \frac{5\vartheta_{13}^2}{8} \\ P_{e\tau} &\approx \frac{3}{16} - \frac{\sqrt{3}}{8}\vartheta_{13}\cos\delta_{\rm CP} + \frac{5\vartheta_{13}^2}{8}\,. \end{aligned} \tag{3}$$

As expected, the survival probability P_{ee} (or equivalently ϕ_e^D) does not depend on $\delta_{\rm CP}$ and the unitarity relation $\sum_\beta P_{e\beta} = 1$ holds at each order in ϑ_{13}. Moreover, the $\bar{\nu}_\mu$ and $\bar{\nu}_\tau$ fluxes depend on $\delta_{\rm CP}$ only via the quantity $\cos\delta_{\rm CP}$. Note that the independence of P_{ee} from ϑ_{23} and $\delta_{\rm CP}$, as well as the relation $P_{e\mu} = P_{e\tau}(\vartheta_{23} \to \vartheta_{23} + \pi/2)$ (which shows up in the opposite signs of the $\cos\delta_{\rm CP}$ terms in Eq. (3)) hold exactly [26]. Though the approximate relations Eq. (3) are useful to grasp the main features of the dependence of the fluxes ϕ_α^D on ϑ_{13} and $\delta_{\rm CP}$, in the following we will use the exact expressions given in Eq. (2). For all numerical examples, we fix the value of the solar mixing angle to $\vartheta_{12} = 32.5°$ [1].

Flavor discrimination in ICECUBE.—Let us now recall briefly the flavor-discrimination possibilities in ICECUBE [27]. For the energies relevant here, 10^{12} eV $\lesssim E \lesssim 10^{15}$ eV, the charged-current interactions of ν_e and ν_τ are in principle only distinguishable by the different muon content in electromagnetic and hadronic showers. In practice, this is an experimental challenge and we consider ν_e and ν_τ as indistinguishable in a neutrino telescope. By contrast, in ν_μ charged-current interactions the long range of muons ensures that the muon track is always visible and allows the identification of these events. Finally, all flavors undergo the same, indistinguishable neutral-current (NC) interactions. This interaction contributes however only 20% to the total cross section [28]. Moreover, in this case the energy of the primary is underestimated by a factor 3–4, further suppressing the relative importance of NC interactions because of the steeply falling energy spectrum. In the following, we neglect therefore NC interaction and consider the combined $\bar{\nu}_e$ and $\bar{\nu}_\tau$ flux $\phi_e^D + \phi_\tau^D$ and the $\bar{\nu}_\mu$ flux ϕ_μ^D as our two observables.

The flux ratio $R = \phi_\mu^D/(\phi_e^D + \phi_\tau^D)$ as only observable does not allow the simultaneous measurement of ϑ_{13} and $\delta_{\rm CP}$. For the sake of clarity, we first explore the sensitivity of R to the value of ϑ_{13}, fixing $\delta_{\rm CP} = 0$. In Fig. 1, we show the expected ratio R as a function of ϑ_{13} for

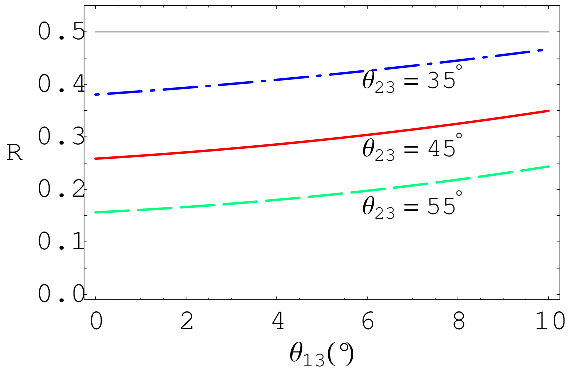

FIG. 1: Flux ratio $R = \phi_\mu^D/(\phi_e^D + \phi_\tau^D)$ at Earth as a function of ϑ_{13} for $\vartheta_{23} = 35°$ (blue, dot-dashed curve), $\vartheta_{23} = 45°$ (red, solid curve), $\vartheta_{23} = 55°$ (green, dashed curve); for initial fluxes $\phi_e : \phi_\mu : \phi_\tau = 1 : 0 : 0$ at the source and $\delta_{\rm CP} = 0$. The ratio $R = 0.5$ expected for standard astrophysical sources is shown for comparison.

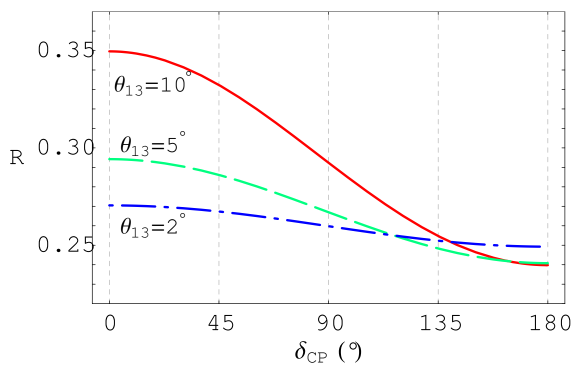

FIG. 2: Flux ratio $R = \phi_\mu^D/(\phi_e^D + \phi_\tau^D)$ at Earth as a function of $\delta_{\rm CP}$ for $\vartheta_{13} = 10°$ (red, solid curve), $\vartheta_{13} = 5°$ (green, dashed curve), and $\vartheta_{13} = 2°$ (blue, dot-dashed curve); for $\vartheta_{23} = 45°$ and initial fluxes $\phi_e : \phi_\mu : \phi_\tau = 1 : 0 : 0$ at the source.

three representative values of ϑ_{23}. This ratio varies by $\sim 50\%$ in the interval $0° \leq \vartheta_{13} \leq 10°$ and differs in the extreme by a factor of three from the standard value, $\phi_\mu^D/(\phi_e^D + \phi_\tau^D) = 1/2$, also shown for comparison.

If the next generation of oscillation experiments measures or strongly constrains ϑ_{13}, a neutrino telescope may even aim to detect leptonic CP violation. In Fig. 2, we show the expected ratio $R = \phi_\mu^D/(\phi_e^D + \phi_\tau^D)$ as a function of $\delta_{\rm CP}$ for three values of ϑ_{13}; we have chosen the best fit value $\vartheta_{23} = 45°$. In this case the ratio varies maximally by about 40% in the interval $0° \leq \delta_{\rm CP} \leq 180°$ and differs in the extreme by a factor two from the standard value 1/2. If we use instead $\vartheta_{23} = 35°$ (55°), the only change would be an overall shift of the three curves by $\Delta R \approx +0.1$ (-0.1).

Event rates in ICECUBE.—The excellent angular resolution of 0.7° expected for ICECUBE applies only for muon induced showers, while for ν_e and ν_τ events the resolution is only about 25° [27]. According to the estimate in Ref. [11], one expects roughly 1.5 atmospheric ν_μ background events per year at $E > 1$ TeV in a window of $1° \times 1°$, i.e. ≈ 2.3 yr^{-1} events in a 0.7° radius around the Cygnus region. This number has to be compared with the $\approx 4\,\bar{\nu}_\mu$ signal events assuming $\vartheta_{23} = 45°$ and $\vartheta_{13} = 0$. A $2\,\sigma$ detection of the $\bar{\nu}_\mu$ flux is then within 1 yr capability of ICECUBE. Rescaling this background number to a cone of 25° opening angle, one expects about 2900 ν_μ background events and 145 background showers. Here we used the fact that the atmospheric neutrino background has a flavor ratio of $\phi_e : \phi_\mu : \phi_\tau \approx 0.05 : 1 : 0$ in the energy range of interest, 10^{11} eV $\lesssim E \lesssim 10^{14}$ eV [29]. The resulting statistical fluctuation of the background shower number is $\sqrt{N} \approx 12$. Thus integrating one year the ≈ 16 yr^{-1} rate from Cygnus one expects a $1.3\,\sigma$ signal hint, or equivalently a $4.2\,\sigma$ measurement in a decade.

Obviously, the poor angular resolution for ν_e and ν_τ events is the most serious obstacle to improve this measurement. If however a future neutrino telescope would be able to increase the shower resolution to, say, 10°, then the same estimate would lead to a $3.3\,\sigma$ detection already in one year of data taking. Theoretical predictions for the neutron spectrum at the source could also be used to optimize the detection strategy. To fit the anisotropy data without introducing a cutoff, the AGASA collaboration required in [13] a source spectrum with $\propto E^{-3}$ or steeper, while the spectral index of the model of Ref. [11] is 3.1. The atmospheric neutrino flux falls with a similar slope: its spectral index is in the range 3–3.7, being steeper at higher energies. Thus, if the $\bar{\nu}_e$ spectrum would be truly harder than the atmospheric neutrino background, the signal to background ratio could be improved by an increase of the threshold energy. Notice also that experimentally, the energy spectrum of the signal events could be more easily measured using the shower events [29].

What happens to our previous estimates if we add some contamination from "conventional" pion decay? If the nuclei photo-dissociation mechanism is the correct explanation for the neutron signal, realistic models as the one for the Cygnus region considered in [11] would led to $\mathcal{O}(10\%)$ flux "pollution". In this case, a shift as low as 0.01–0.02 is expected in the flux ratio R, well within the expected experimental statistical error. An accidental pion contamination of the same order of the expected signal would lead to shifts of $\approx +0.1$ in R: the parameter estimate would then be challenging, but significant constraints on the parameter space would be still possible, in particular when ν-telescopes data could be combined with complementary information from terrestrial experiments. Finally, we want to add a remark on the case when neutrons are generated *mainly* in pp or $p\gamma$ collisions. Since the normalization of the $\bar{\nu}_e$ flux from neutron decay is based on the $\approx 4\%$ anisotropy in the CR data, the number of events in ICECUBE from neutron decay

does not depend on the specific generation mechanism. However, when neutrons are produced in pp or $p\gamma$ collisions, additionally a much larger flux of neutrinos from pion decays with $\phi_e^D : \phi_\mu^D : \phi_\tau^D \approx 1 : 1 : 1$ is expected. Obviously, the background for the ϑ_{13} and $\delta_{\rm CP}$ searches discussed here would therefore drastically increase, while the detection of these galactic point sources by neutrino telescopes would become much easier. A much larger flux and a flavor ratio $\phi_\mu^D/(\phi_e^D + \phi_\tau^D) \approx 1/2$ in ICECUBE would be a smoking gun for the dominance of the pp or $p\gamma$ collision mechanism. Although less exciting from the point of view of neutrino physics, such a measurement would have important consequences for the astrophysical source diagnostics as well as for CR composition studies at $\sim 10^{18}$ eV.

Summary.—It has been argued that the excess of high-energy cosmic rays from the Galactic Plane in the energy range around 10^{18} eV is caused by neutron primaries generated in the photo-dissociation of heavy nuclei. If this model is correct, then the initial flavor ratio of the neutrino flux from the Cygnus region is $\phi_e : \phi_\mu : \phi_\tau \approx 1 : 0 : 0$. Thus Nature may provide in a very cheap way almost pure flavor neutrino beams, that similarly to proposed beta-beam factories [30] might help to deepen our knowledge of the neutrino mixing parameters. In particular, we have shown that the observable ratio $\phi_\mu^D/(\phi_e^D + \phi_\tau^D)$ of track to shower events in a neutrino telescope depends appreciably on the 13-mixing angle ϑ_{13} and the leptonic CP phase $\delta_{\rm CP}$, thus opening a new experimental avenue to measure these quantities.

Obviously, a better theoretical modeling of sources as well as more experimental studies, not only in cosmic rays but also in the photon channel, are highly desirable. Especially worthwhile would be a confirmation of the anisotropy by the Auger observatory [31] and more detailed chemical composition studies by the Kascade-Grande experiment [32].

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[33] We denote with ϕ_α the combined flux of ν_α and $\bar\nu_\alpha$.

[34] In general (see e.g. [26]) $P(\bar\nu_\alpha \to \bar\nu_\beta, \delta_{\rm CP}, V) = P(\nu_\alpha \to \nu_\beta, -\delta_{\rm CP}, -V)$, where V is the matter potential. Since matter effects are negligible and the interference terms sensitive to the sign of $\delta_{\rm CP}$ average out, we can use equivalently $P_{\alpha\beta}$ or $P_{\bar\alpha\bar\beta}$.